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Riparian vegetation recovery after invasive alien tree clearance in the Fynbos Biome

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Abstract

The Working for Water programme is tasked with the important role of controlling invasive alien plants with an assumption that indigenous vegetation will recover naturally. This study assessed vegetation composition and structure following alien clearance in closed-stand invasion of riparian areas and a minimum of two years' passive recovery. Three initial clearing treatments — Fell Only, Fell & Remove and Fell & Burn — were compared to uninvaded Reference conditions. The aim was to ascertain the nature of vegetation recovery, as well as to determine which clearing treatment was most successful in promoting recovery. A Detrended Correspondence Analysis revealed that the Fell & Remove treatment most closely approached the Reference condition while Fell Only and Fell & Burn plots had altered composition and structure. All clearing treatments had significantly lower vegetation cover than the Reference and species composition was altered by invasion and clearance. Important growth forms, such as small (3–10 m) trees were suppressed by felled slash and burning. Although burning was the best method to reduce woody alien species, secondary invasion by alien herbaceous species occurred where natural riparian vegetation did not re-establish. The Fell & Remove treatment is recommended as the best to use in promoting indigenous vegetation recovery, and together with continued alien follow-up control, is able to minimize alien re-invasion of riparian ecosystems. Managers are advised to consider active restoration measures in areas where recovery is likely to be protracted.

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1. Introduction

Closed-stand invasions by alien trees and shrubs threaten fynbos riparian vegetation in the Western Cape by suppressing and replacing indigenous species and altering ecosystem functioning (Richardson et al., 1997; Holmes et al., 2005). The negative impact of alien trees on water resources justifies their removal from water catchment areas and this process has been increased via the national “Working for Water” programme (WfW), which was initiated in 1995 by the Department of Water Affairs and Forestry (DWAF) (Van Wyk, 1987; Dye and

Poulter, 1995; Le Maitre et al., 1996; Van Wilgen et al., 1998; Dye and Jermain, 2004). The Working for Water programme (WfW) seeks to protect and maximize water resources and enhance sustainability by eliminating invading alien plants, thus enhancing ecological integrity, while promoting social equity through job creation for marginalized communities (Van Wilgen et al., 1998).

Riparian vegetation in the winter rainfall region of the Fynbos Biome is mainly impacted by Australian *Acacia* (e.g. *Acacia mearnsii*, *A. longifolia*, *A. saligna*) and *Eucalyptus* (e.g. *E. camuldulensis*) species (Forsyth et al., 2004; Nel et al., 2004; Richardson and Van Wilgen, 2004). Riverine ecosystems are highly prone to invasion by alien plants due to the dynamic hydrological nature of rivers and the ease with which propagules are transported along rivers, therefore alien populations easily become established in the riparian zone (Pyšek and Prach,

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1993; Planty-Tabacchi et al., 1996; Hood and Naiman, 2000). The combination of human and natural disturbances further increases the potential for alien species to become established (Richardson et al., 2007). Along Western Cape rivers, alien acacias form dense stands that largely exclude the indigenous fynbos closed-scrub vegetation (Boucher, 2002; Holmes et al., 2005).

Alien clearing operations can succeed or fail to facilitate indigenous vegetation recovery and there has been a call for an improved understanding of the impacts of clearance in order to improve operational efficiency and effectiveness (Versfeld et al., 1998; Holmes et al., 2005). The current management practice by WfW is to reduce above-ground biomass of alien species by labour intensive means, after which indigenous vegetation is usually left to recover without further intervention (Macdonald, 2004). This approach works well in some situations (Derek Malan pers.comm. 2006), and the recovery of vegetation structure can be assumed to result in the appropriate delivery of ecosystem services (King and Hobbs, 2006). In other cases, however, the clearance of aliens leads to re-invasion by the same or secondary alien species (Holmes and Richardson, 1999; Galatowitsch and Richardson, 2005) or a protracted recovery of indigenous vegetation with suboptimal ecosystem functioning (Harms and Hiebert, 2006) thereby suggesting the need for active restoration plans (Macdonald, 2004).

Alien clearance is considered the first step in restoring natural vegetation structure and plant species richness and diversity (Holmes and Cowling, 1997a,b). The reduction of alien propagules and re-establishment of indigenous species may increase the resistance of the site to re-invasion. Ultimately, the success of any alien clearing operation is measured by the recovery of indigenous vegetation (Holmes and Richardson, 1999).

During clearing operations, alien trees are felled as close to the base as possible and herbicide is applied to stumps of re-sprouting species. In some cases large trees are killed by herbicide stem injection (frilling) (Anon, 2000; Galatowitsch and Richardson, 2005). Burning is considered a useful tool to kill non-re-sprouting aliens, reduce alien soil-stored seed, remove excessive above-ground biomass (slash) following felling and initiate indigenous fynbos vegetation recovery. However, hard-seeded alien species are stimulated to germinate by fire, therefore sufficient resources should be allocated to follow-up treatments to reduce the potential spread of these alien species (Holmes et al., 2000; Pieterse and Boucher, 1997). Re-invading alien species are usually managed by hand-pulling or foliar herbicide application if the plants are below 1 m, or felling if taller than 1 m. Biological control is a longer-term method for controlling an alien species. Most of the alien *Acacia* species that invade Fynbos Biome riparian zones have biological control agents established on them. However, these mainly reduce the viable seed output of aliens and reduce their rate of spread (Van Wilgen, 2004; Zimmermann et al., 2004). The degree of control achieved by these biocontrol agents range from negligible to complete. The dominant riparian invader in the Fynbos Biome, *A. mearnsii*, has a seed-attacking biocontrol agent, but the impact of the agent currently is unknown. In the

case of “complete control”, viable seed production is reduced to the extent that plants are no longer invasive. However, existing stands generally still require mechanical or chemical control (Zimmermann et al., 2004).

This is the first study to investigate the impacts of different clearing methods on riparian vegetation recovery in the winter rainfall region of the Fynbos Biome. The study focuses on the most densely invaded areas. We address the following questions:

- 1) Are there differences in floristic and growth form composition between Reference non-invaded vegetation and alien-cleared vegetation?
- 2) Are there differences among plots cleared by different methods?
- 3) Which clearing method best facilitates indigenous vegetation recovery?

Based on the results of the study, we make recommendations for improving the restoration potential of alien-invaded riparian zones in winter rainfall areas of the Fynbos Biome.

2. Materials and methods

2.1. Experimental design

We sampled a range of riparian sites in the mountain stream and foothill reaches of different rivers across the winter rainfall region of the Fynbos Biome (Fig. 1). The study compared Reference (control) sites to alien-impacted sites in order to analyse variation among vegetation variables. Reference sites have often been used in rehabilitation and restoration efforts to provide recovery goals (e.g. Buijse et al., 2002). Environmental variables (soil depth, altitude, soil texture, pH, % rock cover) were included to help determine the natural variation among sites. It was acknowledged *a priori* that it would be difficult to relate vegetation recovery response solely to the clearing treatment. A number of important factors influence plant colonization and establishment, such as duration of invasion and extent of landscape transformation. However, by using a large sample size, it was anticipated that the impact of different clearing treatments would exceed the natural variation among sites and river catchments.

We sampled 78 alien-cleared sites along fifteen rivers (Fig. 1; Table 1). These sites were compared to 69 Reference sites, 8 of which were sampled in this study and 61 in an earlier study sampled in 1999 (Prins et al., 2004; Table 1). The same sampling method was applied to allow for comparisons between the two studies. More than one plot was sampled per river, but plots were located at least 200 m apart to provide a measure of independence (Galatowitsch and Richardson, 2005).

Three different clearing treatments were investigated, namely Fell Only, Fell & Remove and Fell & Burn (Table 1). The three treatments differ in their handling of slash. In Fell Only, trees are felled and slash is left on site. In Fell & Remove, slash is removed from the riparian zone. In Fell & Burn, the slash is left for six months to a year before it is burnt. These initial treatments

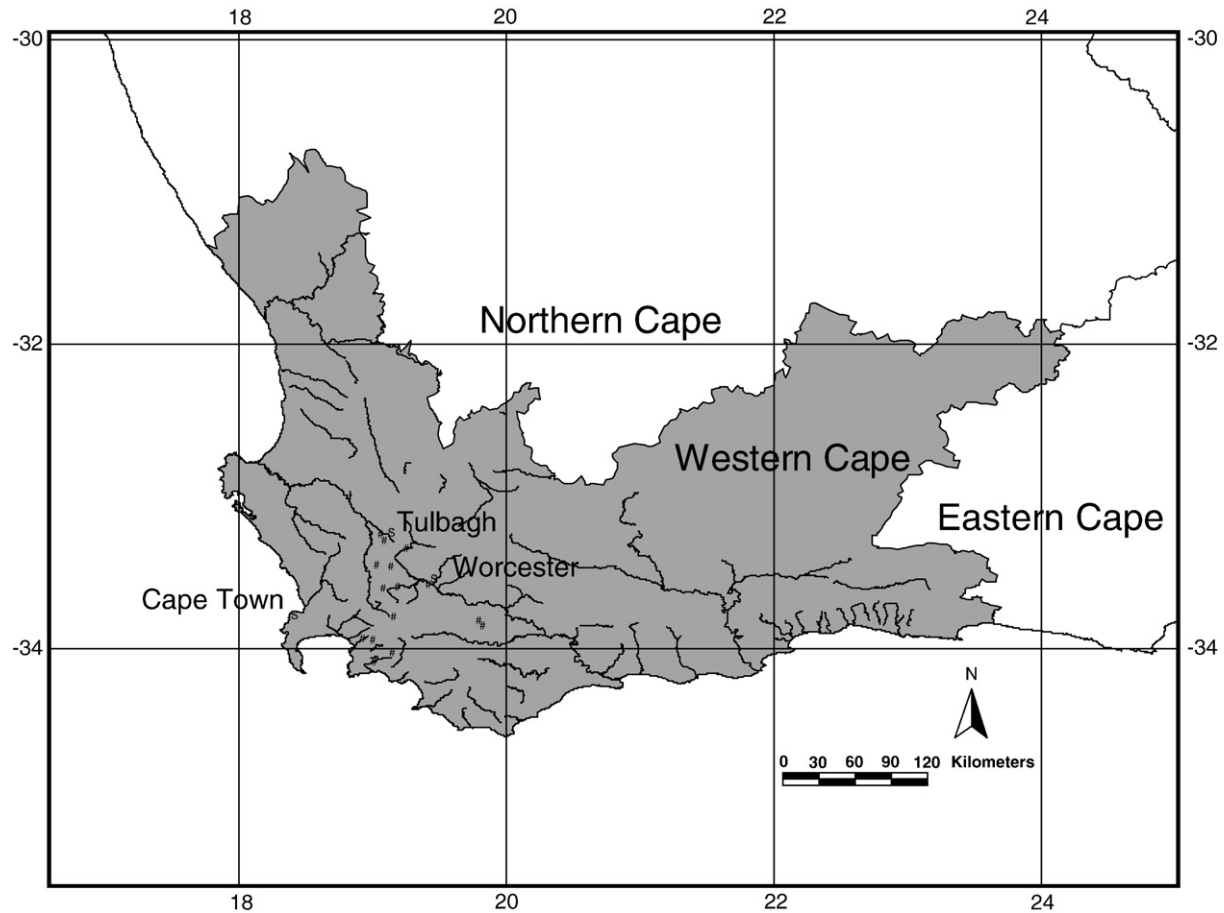


Fig. 1. Map of the Western Cape, South Africa, showing the fifteen rivers sampled which fall within the winter rainfall region of the Fynbos Biome. Characteristics of the 78 study sites (●) are provided in Table 1.

had been applied at least two years prior to sampling to allow for sufficient time for some post-clearance vegetation response.

Potential sites were located using the WfW database (Marais *et al.*, 2004) and then confirmed by discussions with CapeNature

and DWAF alien clearing project managers. Management histories were collected from records kept within each department. These included initial clearing method, dominant alien plant species and densities, dates of initial clearance, follow-up

Table 1

Locations of study plots for each of the three clearing treatments along Western Cape rivers and the Reference plots[^] used as baseline data

Clearing treatment	River name	No. of plots sampled	Reference plots	Map reference	Altitudinal range (m)	Mean annual rainfall (mm)	Year of initial treatment
Fell & Remove	Molenaars	4	21 (i)	3319CA	300–340	889	2002–2003
	Waterval	8	2* (ii)	3319CA	220–300	600	1998–1999
	DuToits Kloof	6	(i)	3319CA	560–590	1477	1997–1998
	Witte	4	26 (iii)	3319CA	260	833	1998
Total		22					
Fell Only	Palmiet	2	14 (iv)	3419AC	130	817	1997
	Wesselsgat (Palmiet upper)	5	(iv)	3419AA	330	1285	1999
	Breede	6	(i, iii)	3319AC	200	299	2003
	Klein Berg	6	(ii)	3319AC	90–120	552	1998
Total		19					
Fell & Burn	Jakkals	13	(iv)	3419AA	190–250	875	1997–1998
	Hoeks	4	2*	3319DD	240–280	263	2001
	Houtbaais	3	2*	3319DD	250–280	247	2001
	Assegaaibos	2	1*	3319CA	300	531	2003
	Viljoens	1	(iv)	3319CC	360	901	1999
	Titus	10	(i, iii)	3319AD	290–320	655	1998–1999
	Sir Lowry	4	1*	3418BB	220–290	966	2002
Total		37					

[^] Reference data taken from Prins *et al.* (2004) was used as baseline data for cleared rivers and close neighbours.

* Additional reference plots sampled in this study.

method and dates, and whether burning was included in the initial treatment.

Sites of moderate to dense alien infestation (25–75% canopy cover) generally have sufficient indigenous vegetation remaining to facilitate unaided recovery (Galatowitsch and Richardson, 2005), so the focus of this study was on the closed-stand alien invasion (>75% canopy cover) where natural recovery may be protracted.

To allow for comparison with the Reference survey, vegetation plots measuring 10×5 m were set up in the riparian zone, with the long edge parallel to the river (Prins et al., 2004). Because different lateral riparian zones have been identified in fynbos rivers (Boucher, 2002), we chose to standardise sampling by locating the sample plots in the major dry bank zone as the wet bank sometimes is very narrow. Alien trees invade both the wet and dry bank lateral riparian zones, with the dry bank riparian scrub zone being the more susceptible to woody alien species (Boucher, 2002).

2.2. Data collection

Within each plot, total indigenous vegetation cover was estimated as a percentage of the entire plot (50 m^2), while vegetation composition was measured using estimated percentage projected canopy cover values for individual perennial plant species (indigenous and alien) present within the plot. Indigenous species richness was recorded in three 1 m^2 quadrates within the plot, as well as for the entire 50 m^2 plot. All recognizable species were collected in the field and specimens taken for identification in the herbarium. Nomenclature follows Goldblatt and Manning (2000).

Species were assigned to growth forms based on morphology and maximum height reached, as described by Goldblatt and Manning (2000). The four broad growth form classes are forbs (herbaceous dicotyledonous plants), graminoids, shrubs and trees. The narrow growth form classes comprised forbs, graminoids (divided into restioids and other graminoids:

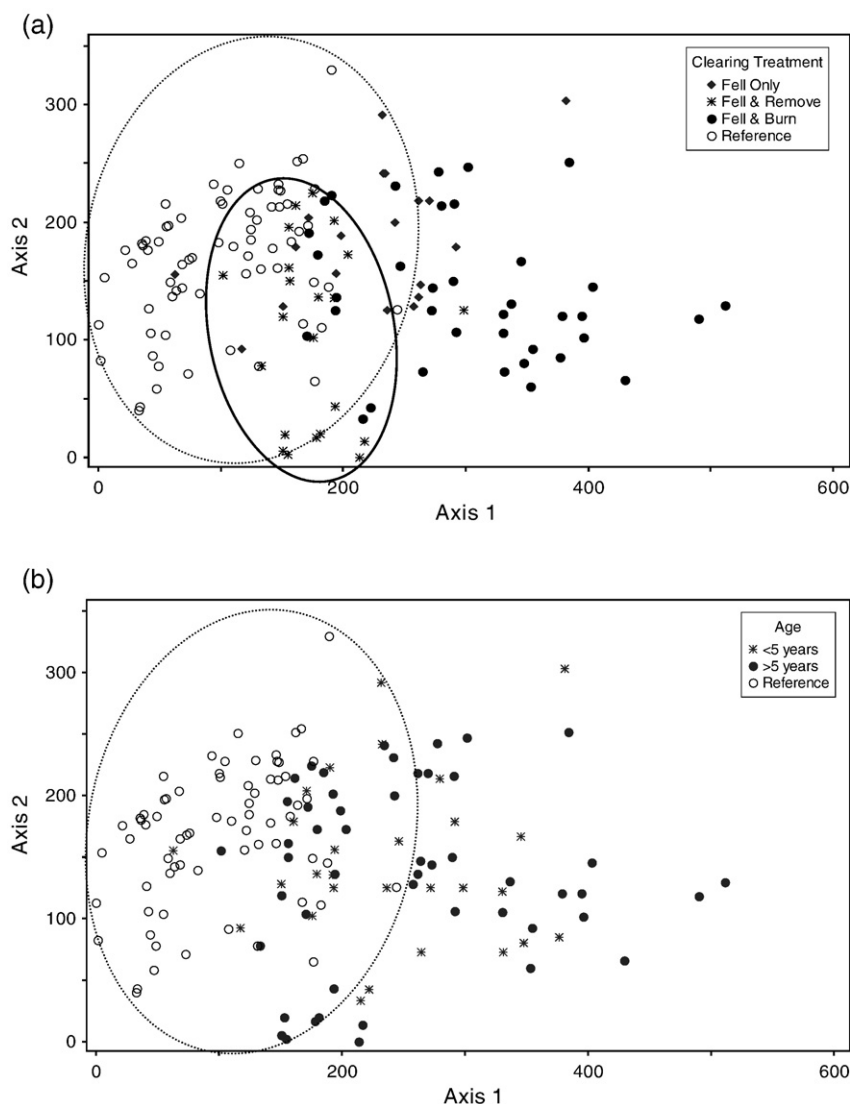


Fig. 2. Detrended Correspondence Analysis ordination of all sample plots based on indigenous perennial species with infrequent species down-weighted. a) Plots grouped according to clearing treatment. b) Plots grouped according to age since clearance. The ellipses encompass the Reference plots (dotted lines) and Felled & Remove plots, except for one outlier (solid line).

Table 2
Effects of clearing treatments on vegetation variables showing mean \pm standard error

Vegetation variables	Fell Only	Fell & Remove	Fell & Burn	Reference
<i>N</i>	19	22	37	69
<i>Indigenous vegetation</i>				
% canopy cover	41.3 \pm 5.96 ^a	66.89 \pm 4.39 ^b	54.2 \pm 4.23 ^{ab}	73.1 \pm 1.40 ^c
Species richness *1 m ²	1.72 \pm 0.21 ^a	3.10 \pm 0.31 ^{bc}	2.16 \pm 0.13 ^{ab}	4.48 \pm 1.19 ^c
Species richness 50 m ²	9.11 \pm 0.98 ^b	15.5 \pm 1.29 ^a	11.2 \pm 0.70 ^b	11.0 \pm 0.57 ^b
Shannon diversity index	1.34 \pm 0.13 ^a	1.88 \pm 0.08 ^c	1.51 \pm 0.05 ^{ab}	1.70 \pm 0.05 ^{cb}
Evenness	0.58 \pm 0.06 ^a	0.81 \pm 0.04 ^{ab}	0.66 \pm 0.02 ^a	0.74 \pm 0.03 ^b
<i>Alien cover</i>				
% canopy cover woody species	21.7 \pm 6.18 ^a	17.5 \pm 4.24 ^a	5.03 \pm 1.25 ^b	1.92 \pm 0.50 ^b
% canopy cover herbaceous species	7.87 \pm 2.83 ^{abc}	2.30 \pm 1.57 ^a	14.4 \pm 3.73 ^{bc}	0.05 \pm 0.03 ^a

Within each variable, columns with different letter superscripts are significantly different.

* 1 m² plots were only measured for plots sampled in the current survey (*N*=8). These exclude the reference plots surveyed by Prins et al. (2004).

including sedges, rushes and grasses), shrubs (divided into three height classes: <1 m shrubs, 1–2 m shrubs, and >2 m shrubs) and trees (divided into two height classes: 3–10 m-tall trees and >10 m-tall trees). It was decided that restioids (species belonging to the Restionaceae family) be separated from other graminoids, as they are an important descriptive feature of riparian zones in the Fynbos Biome (Taylor, 1978). Indigenous species were further classified according to regeneration mode (namely: re-sprouter, short-lived (≤ 4 years) obligate seeder, long-lived (≥ 5 years) obligate seeder) following Holmes and Cowling (1997a) and from expert knowledge (T. Trinder-Smith, pers. comm.).

Altitude was measured using a Garmin GPS IV instrument, and average soil penetrability (a surrogate for depth) estimated by hammering a steel rod into the soil until reaching an impenetrable layer at five random points per plot. A soil sample was taken from each plot comprised of five (approximately 100 ml) subsamples mixed together from the first 50 mm of soil immediately beneath the litter layer. The samples were air dried and sent to the Soil Science Division, Department of Agriculture (Private Bag X1, Elsenburg, 7607) for analysis of pH and soil texture (percentage fine, medium, coarse sand). The percentage cover of surface rocks in each plot was noted.

2.3. Data analysis

The effects of the three different clearing treatments (Fell Only, Fell & Remove, Fell & Burn) on vegetation variables (total indigenous cover, indigenous species richness and diversity, alien cover) were compared to the Reference plots using one-way analysis of variance (ANOVA as provided in Statistica version 7). Where data were not normally distributed, appropriate transformations were applied. Indigenous vegetation cover percentages were Arcsin transformed. Species richness (50 m² and 1 m²) and Shannon–Wiener diversity indices were square-root transformed.

Where ANOVA's were significant, Tukey's HSD unequal *n* test was used to determine variance at $P < 0.05$. Richness at the 1 m² scale was not included in the Prins et al. (2004) survey that supplied the majority of data for Reference plots, thus only the few Reference plots (*n*=8) surveyed in this study could be used.

Where normality was not achieved after the appropriate transformation, the non-parametric Kruskal–Wallis test was used, as it makes no assumptions about the homogeneity of variance or the normal distribution of data (Dytham, 2005; Zar, 1996). This test was used to investigate differences among clearing treatments for diversity indices, which failed to conform to ANOVA assumptions.

The effect of age since clearance on vegetation recovery was examined by dividing the cleared plots into two age groups for each clearing treatment (those cleared <5 years ago and those cleared ≥ 5 years ago). Two-way ANOVA was used to

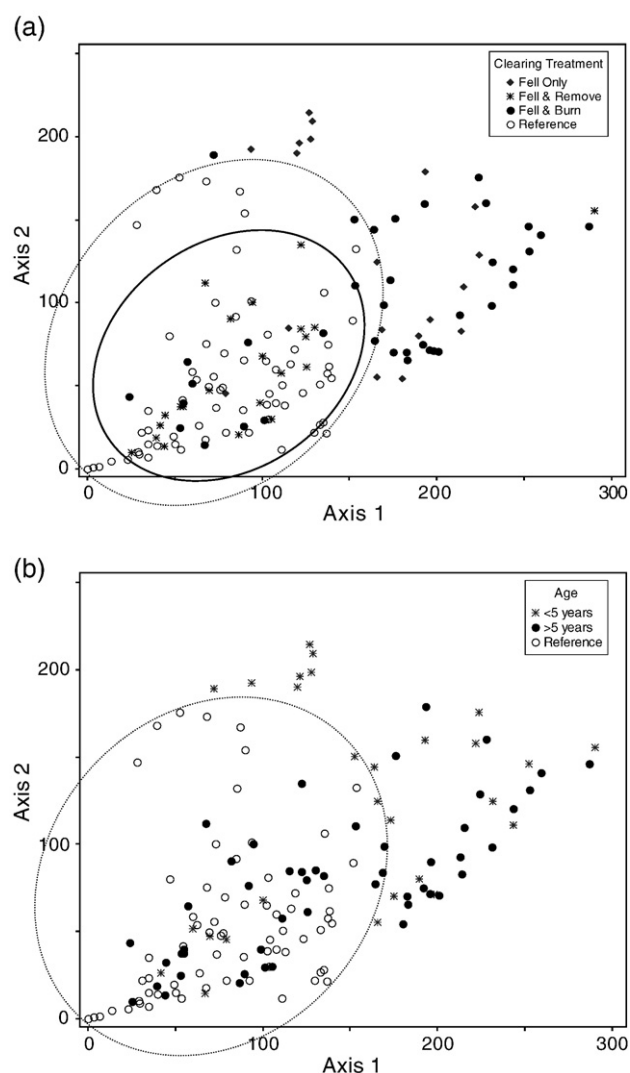


Fig. 3. Detrended Correspondence Analysis ordination of all sample plots based on eight narrow growth forms. a) Plots grouped according to clearing treatment. b) Plots grouped according to age since clearance. The ellipses encompass the Reference plots (dotted lines) and Fell & Remove plots, except for one outlier (solid line).

determine any interaction effects of age since clearance and clearing treatment. Where relationships were significant, multiple range tests were used to assess the differences.

Diversity per 50 m² plot was assessed using cover values per species as a proportion of the total vegetation cover calculated for the Shannon–Wiener (H') index and Evenness index using “Pielou’s J ” (McCune and Grace, 2002; Zar, 1996).

$$H' = - \sum_{i=1}^k p_i \ln p_i$$

where k =number of species and p_i =the proportion of species found in plot i .

$$J = \frac{H'}{H'_{\max}} \quad \text{and} \quad H'_{\max} = \log k$$

Detrended Correspondence Analysis (DCA) was used to analyse differences in plant community composition caused by specific management treatments using PC-Ord 4.0 (MjM Software Design, 1999). PC-Ord contains the updated version for the algorithm used in the DCA ordination (McCune and Grace, 2002). DCA ordinations have been successfully used in testing the recovery of diversity in restoration experiments (Ruiz-Jaen and Aide, 2005). The distance between communities in ordination space is a measure of their compositional dissimilarity (Shaw, 2003), making it possible to note the direction and extent of changes in composition. Species composition, as determined by percentage projected cover of individual species, was converted to Braun–Blanquet cover-abundance scores for analysis in the ordination (Werger, 1974) to align with the Prins *et al.* (2004) study. Correlations of species and environmental variables (soil depth, altitude, soil texture, pH, % rock cover) were associated with the ordination axes using Pearson’s correlation coefficient (r) in the PC-Ord package.

3. Results

3.1. Vegetation composition

The results from a DCA species ordination indicated that there was considerable overlap between the Reference and Fell & Remove plots, except for one slightly outlying group from the Tulbagh area (Fig. 2a). Fell Only plots overlapped to a lesser extent with the Reference plots. However, Fell & Burn plots overlapped the least with Reference plots and were much more widely scattered indicating greater variability in composition. Pearson’s correlation revealed that species richness ($r=-0.521$) and vegetation cover ($r=-0.520$) were negatively correlated with Axis 1, whereas % fine sand ($r=0.639$), soil depth ($r=0.461$) and alien cover ($r=0.411$) were positively correlated. Axis 2 had a weak positive relationship with pH ($r=0.404$). Fig. 2b showed that a large proportion of burnt plots were older than 5 years and had still not approached the Reference condition.

Indigenous species richness was shown to differ significantly at the 50 m² scale ($F_{(3,144)}=6.09$; $P<0.001$) and at the 1 m² scale ($F_{(3,82)}=15.0$; $P<0.01$; Table 2). None of the clearing treatments exhibited significantly lower richness than the Reference plots at the 50 m² scale: Fell & Remove plots had significantly greater species richness than Fell Only, Fell & Burn and Reference plots. However, at the 1 m² scale, Tukey’s test revealed Reference plots to be significantly richer than Fell Only and Fell & Burn treatments. Clearing treatments also differed at the 1 m² scale, with Fell & Remove plots having significantly higher species richness than Fell Only plots.

Diversity measures differed significantly among treatments for both Shannon–Wiener (Kruskal–Wallis $H_{(3)}=14.9$; $P<0.001$) and Evenness indices (Kruskal–Wallis $H_{(3)}=23.6$; $P<0.001$; Table 2). The Fell & Remove treatment recorded the highest diversity and was significantly different to Fell Only and Fell & Burn, but not to the Reference plots. The Fell Only

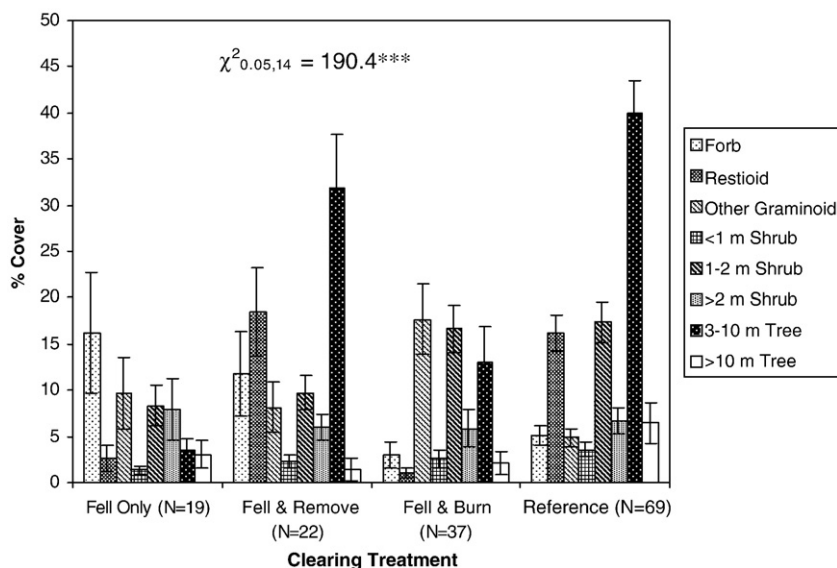


Fig. 4. Projected % canopy cover for eight narrow growth forms (mean±standard error) in cleared and Reference plots. The χ^2 analysis was calculated using contingency tables with Reference as the expected values.

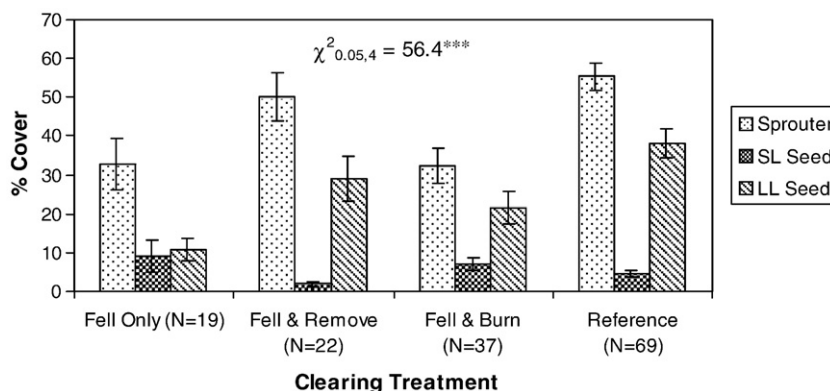


Fig. 5. Projected % canopy cover for regeneration mode guilds in cleared and Reference plots (mean \pm standard error). Where: SL = short-lived seeder (≤ 4 years), LL = long-lived seeder (≥ 5 years). The χ^2 analysis was calculated using contingency tables with Reference as the expected values.

treatment was the only treatment to have significantly lower diversity than the Reference condition. The Reference plots had significantly higher evenness scores than Fell Only and Fell & Burn plots, but not compared to Fell & Remove plots.

3.2. Vegetation structure

There were significant differences in indigenous perennial vegetation cover among treatments (ANOVA; $F_{(3,144)} = 39.9$; $P < 0.001$; Table 2). A Tukey's test indicated that the Reference plots had higher cover than all the clearing treatments. Differences were apparent among clearing treatments, as Fell & Remove plots had significantly higher indigenous cover than Fell Only plots, with Fell & Burn an intermediate between the two.

The DCA ordination applied to the four broad growth forms revealed that cleared plots were more similar in structure to the Reference plots than indicated by species composition. However, the eight narrow growth forms revealed differences similar to that of species composition (Fig. 2) in that the majority of Fell & Remove plots clustered with the Reference group, while many of the Fell Only and Fell & Burn plots clustered farther away (Fig. 3). Pearson's correlation revealed that graminoid and small tree cover were correlated with axis 1 ($r = 0.596$ and $r = -0.760$ respectively) while forb, tree and small tree cover were correlated with axis 2 ($r = 0.478$, $r = 0.400$ and $r = -0.569$ respectively). The growth forms DCA axis 1 was positively associated with the environmental variables of % fine sand and soil depth ($r = 0.417$, $r = 0.444$ respectively) and negatively with altitude and species richness ($r = -0.499$, $r = -0.382$ respectively). Axis 2 has no strong environmental correlates.

The different treatments had varying proportions of the eight narrow growth forms that were significantly different to the Reference plots ($\chi^2_{(3,14)} = 190.4$, $P < 0.001$; Fig. 4). The three prominent growth forms in the Reference plots were: restioid, 1–2 m shrubs and 3–10 m trees. The high restioid cover was matched only in the Fell & Remove plots, whereas Fell Only and Fell & Burn had considerably lower restioid cover. Fell & Burn treatments had similar cover of 1–2 m shrubs to the Reference plots, whereas Fell Only and Fell & Remove had

lower cover. The cover of 3–10 m trees was lower in all cleared treatments compared to the Reference plots, although the Fell & Remove treatment most closely approached the Reference for this growth form. Other growth forms that increased in cleared plots were forb cover in unburnt plots and an increase in other graminoids (e.g. Poaceae and Cyperaceae) in Fell & Burn treatments, which far exceeded that of the other clearing treatments (Fig. 4).

The relative importance of resprouters in riparian communities is indicated in Fig. 5, as this guild had the highest cover in all treatments. Long-lived seeders were under-represented in cleared plots when compared to the Reference, with Fell & Remove having the highest cover of this guild among clearing treatments.

Time since clearance had an impact on indigenous vegetation cover as older plots had higher cover than younger plots (Students t -test; $t = 1.13$; $P < 0.001$). This was further investigated using age since clearance and clearing treatment as the two factors in a two-way ANOVA analysis. Although there was a trend for increased vegetation cover over time, differences within treatments were non-significant (Two-way ANOVA; $F_{(2,72)} = 0.604$; $P > 0.5$; Table 3).

Mean alien cover within Fell & Remove and Fell & Burn was 20%, whereas Fell Only had a mean of 30% alien cover (Table 2). Reference plots had a negligible cover of alien species. Although Fell & Remove and Fell & Burn treatments

Table 3

Two-way analysis of variance table for the variables of vegetation cover and species richness, with age since clearance and clearing treatment as the two factors

Factor	d.f.	SS	P	F
Vegetation cover				
Age since clearance	1	2200.5	0.004	8.82
Clearing treatment	2	8.78.8	0.179	1.76
Interaction	2	301.4	0.549	150.7
Error	72	179,584.4		
Species richness				
Age since clearance	1	0.1543	0.538	0.382
Clearing treatment	2	4.60	0.005	5.703
Interaction	2	5.39	0.002	6.676
Error	72	29.07		

had similar total cover of alien species, Fell & Burn alien cover was comprised mainly of herbaceous species. Both Fell Only and Fell & Remove plots contained more woody alien cover, mainly comprising the cleared alien species targeted in the initial clearing operation.

4. Discussion

4.1. Comparisons between Reference and alien-cleared vegetation

The experimental design comprised a natural experiment, using available sites from an active alien plant clearance programme rather than a controlled field experiment. Natural background variation was anticipated to be high, and so interpretation of the results is limited to some extent by a lack of information on post-clearance activities, especially the type and numbers of follow-up controls applied. Reference areas that have not been invaded and cleared have higher indigenous canopy cover than invaded and cleared areas. The significantly lower indigenous cover for cleared plots is consistent with other studies where alien vegetation has been removed from riparian zones (Galatowitsch and Richardson, 2005; Harms and Hiebert, 2006). Similarly, and as expected, the Reference areas have lower alien cover than invaded and cleared areas. The lower indigenous vegetation cover within cleared plots was compensated for by the presence of alien cover. Since the study looked at early recovery (2–10 years), it is anticipated that the slow growing riparian species that have survived invasion and clearing will increase their cover as time progresses. In all four diversity measures investigated, the Fell & Remove treatment met or exceeded the Reference values, and for richness at the plot scale, all clearing treatments matched that of the Reference, suggesting that post-clearance recovery of plant biodiversity is feasible. Plot species richness in the Fell & Remove treatment exceeded values for the Reference plots, suggesting that disturbance-related change results in a temporary increase in species richness, attributed to short-lived pioneer and surviving re-sprouter species (Holmes and Foden, 2001; Davies et al., 2005; Wolters et al., 2005), and may be indicative of an earlier successional stage in cleared plots. A riparian seed bank study indicated that seeds of forb, graminoid and some shrub species persist in the soil at invaded sites (Vosse et al., 2008-this issue).

Overlap in ordination space between some cleared and Reference plots, suggests that passive vegetation recovery is possible post-clearance and a positive trajectory towards recovery of ecosystem structure and composition can be expected. The Fell & Remove treatment performs best, while the presence of excessive slash (Fell Only) and the burning of slash (Fell & Burn) reduce the extent of recovery in alien-impacted fynbos riparian ecosystems.

In the Fell Only and Fell & Burn treatments, the loss of typical riparian scrub cover (3–10 m trees) in cleared plots confirms similar findings (Galatowitsch and Richardson, 2005), indicating either that mature trees do not survive invasion or are cleared indiscriminately during clearing operations (Holmes and Cowling, 1997b; Reinecke et al., 2008-this issue).

Galatowitsch and Richardson (2005) further suggest that riparian scrub species only colonize stable banks and rock fractures, suggesting that open, fire-prone environments are likely to be unfavourable for their recruitment. However, once riparian scrub species are established in these areas, they have the capacity to re-sprout following fire and persist in the vegetation (Holmes, 1998; Pretorius et al., 2008-this issue). Colonization from seed by these species may only take place once an initial pioneer herbaceous and shrub layer has sufficiently stabilized the river banks and insulated the soil surface from extreme conditions. Thus the immediate recovery of cleared areas is assessed based on surviving indigenous species (e.g. *Brabejum stellatifolium*, *Brachylaena neriifolia*) or plants germinating from the soil-stored seed bank (Vosse et al., 2008-this issue). Further development of the riparian zone would depend on the dispersal of overstorey species via water and vertebrate vectors, provided that the propagules are present within the sub-catchment.

Environmental correlations with the DCA axis suggest historical land-use, topography and invasion history all contribute to the recovery of the cleared site and are a function of positioning in the landscape. It is difficult to determine a cause for differences in recovery for cleared sites using the environmental variables sampled in this study.

4.2. Comparisons among different clearing treatments

Differences in clearing treatments are apparent as the Fell & Remove treatment reflected results closer to the Reference plots than the other two treatments when assessing vegetation cover, species and growth form composition and diversity. The reduction in vegetation cover for both Fell Only and Fell & Burn treatments suggests that increased biomass, via slash, and burning in the riparian zone negatively affects indigenous vegetation cover in the short term (2–10 years). Of all the treatments investigated, the Fell & Remove treatment resulted in a vegetation composition and structure most similar to that of the Reference condition. The removal of slash from cleared areas probably allows species to take advantage of disturbed and open conditions (Dickinson and Kirkpatrick, 1987). In the case of fynbos riparian ecosystems, these openings mimic natural disturbances (fire, erosion) in providing some of the germination cues required by indigenous seed in the soil seed bank.

The Fell Only treatment resulted in the lowest indigenous vegetation cover, diversity and richness at point and plot scales. The most likely explanation is that the felled slash inhibits germination cues of species surviving in the soil seed bank.

In all cases, plots receiving the Fell & Burn treatment were least similar to the Reference plots, owing to their very different species composition and in particular a dearth of restioids and small, riparian scrub trees and a high cover of grasses. Natural fires do burn riparian scrub vegetation, and the vegetation has a natural resilience to this through the re-sprouting capability of species from epicormic or basal stem buds. In the control of alien acacias, that accumulate large stores of hard-coated seed, burning is a useful method for reducing their seed bank by increasing mortality and triggering mass germination (Pieterse

and Cairns, 1986; Holmes et al., 1987). However, high-severity fires may occur if the slash fuel load far exceeds the natural fuel load and is not removed from the site prior to burning. Such high-severity fires may cause a loss of species and a reduction in seedling density (Euston-Brown et al., 2002). They may also kill persisting riparian scrub species and set the succession back to a stage requiring initial colonization by pioneer species. Similar effects have been reported from Ponderosa pine plantations, where slash piles are accumulated and burnt (Korb et al., 2004). Soil chemistry may also be altered and seed viability decreased (Korb et al., 2004), suggesting that fires should be avoided where unnaturally high fuel loads are present (Breytenbach, 1989). Instead, biomass should be removed from the river corridor and, perhaps, sold as firewood to offset some of the costs. Where this is not feasible, stacks of unwanted biomass could be burnt on exposed sandbars during low flow periods or on existing roads (Korb et al., 2004; Holmes et al., 2005), thereby avoiding the negative impacts of fire on any surviving indigenous vegetation.

An indirect impact of the Fell & Burn treatment, via the increased density of aliens (particularly *Acacia* species) germinating after fire (Pieterse and Boucher, 1997), is that it promotes the use of broad-scale herbicide foliar application in follow-up control activities. This practice has a significant negative impact on any germinating or re-sprouting indigenous dicotyledonous species which are usually killed in the process (Parker-Allie et al., 2004). Stricter protection of indigenous seedlings during follow-up operations could counteract this potential negative impact of the Fell & Burn treatment.

In conclusion, alien clearing operations are succeeding in reducing alien cover within riparian areas. However, the rate of vegetation recovery may be negatively impacted by insufficient follow-up control and a change in invader-species composition, especially following a burning treatment. The Fell & Remove treatment performs better than the other two clearing treatments. The removal of slash without burning promotes the recovery of common riparian species. Although the vegetation cover of these plots is still lower than the Reference condition, vegetation structure and species composition are similar and it appears that most plots are on a trajectory towards recovery. It is unlikely that propagule pressure (either from soil-stored seed banks or dispersing propagules) differed between these two treatments, so the most likely explanation is that biomass removal promotes the growth of re-establishing species and possibly provides a larger number of establishment niches. If biomass levels are unnaturally high, however, the risk of a severe wild fire may also be high with a potentially negative impact on vegetation recovery. Re-sprouting of alien species is common in areas where excessive biomass hinders ground-level felling of alien species in follow-up operations. For these reasons, biomass removal (of especially the larger pieces) is recommended.

4.3. Future research

This study revealed the importance of long-term monitoring especially in areas where passive recovery is expected to take

place, such as the riparian areas of the Fynbos Biome. Further studies are required to investigate the impacts of secondary alien invasions on indigenous vegetation recovery. Where alien grasses such as Kikuyu (*Pennisetum clandestinum*) invade following alien tree clearance, especially following burning, the regeneration niche may be usurped, further delaying vegetation recovery (Reinecke et al., 2008-this issue).

The influence of the surrounding landscape in supplying propagules is also likely to be important in influencing recovery rate (Petit and Froend, 2001; Galatowitsch and Richardson, 2005; Holmes et al., 2005). This is especially important since riparian seed bank analysis by Vosse et al. (2008-this issue) revealed the limited recruitment that can be expected from this source for the dominant riparian scrub species. Therefore an improved understanding of the dispersal characteristics (e.g. water versus vertebrate) and germination requirements of key riparian scrub species is important. Regarding a recent survey of riparian zones, the poor conservation status of most rivers could indicate poor recovery potential of extensively disturbed areas, as nodes of climax riparian vegetation are likely to be reduced (Nel et al., 2007). Active restoration is considered difficult and expensive (Hobbs and Norton, 1996; Holmes, 2002; Macdonald, 2004) and it is unlikely to restore all elements missing from a degraded system. Nevertheless, this should be considered, as the change in vegetation structure from riparian scrub to low graminoid and herbaceous cover could result in changes to ecosystem services (e.g. water quality) that might be associated with a loss of dominant riparian scrub species (Richardson et al., 2007).

It was not possible in the time frame of this study to determine the economic costs and benefits of the different clearing treatments used. However, the hidden costs of leaving slash *in situ* could far outweigh the costs of slash removal due to unforeseen events, such as increased fire intensity, reduced recovery potential and the possibility of damage caused by such excess slash during flood events. Where a site is close to a road, there is good potential for the larger wood to be sold for firewood or other uses to offset the costs of removing from the site. An analysis of costs and benefits would further assist management decisions.

4.4. Recommendations for improving restoration potential of invaded riparian zones

Our results indicate that passive recovery of fynbos riparian scrub is likely to occur in a relatively short time frame (<10 years) following the clearance of dense aliens, provided a Fell & Remove treatment is applied. Invaded sites cleared by the other methods may take a longer time to resemble the Reference condition in structure and composition. Indigenous species present within densely invaded areas should be protected from accidental clearing, damage from felled alien slash and herbicide overspray as far as possible. Once the aliens are felled, the preferred option is to remove the biomass, especially the large-diameter wood. If this is not feasible, the slash should be thinned or stacked, to allow space for some vegetation recovery between stacks, and the stacks either left

to rot (and burn in the next fire that sweeps the area) or else burn under conditions that cause minimal ecosystem damage (Holmes and Foden, 2001; Behenna et al., 2008-this issue). In the case of stacks below the winter flood-line, burning should be done prior to the winter rains. However for higher-lying stacks, less soil damage will occur if burning is done after heavy rain when the soils are wet.

Some riparian scrub species require stable conditions to establish. Therefore limiting the disturbance experienced within cleared areas and promoting indigenous pioneer woody and herbaceous cover may provide suitable establishment sites for characteristic riparian species. Applying this approach to areas where recovery has been protracted, especially those cleared >5 years ago could help set riparian areas on a trajectory towards recovery. These recommendations for WfW have been devised for the winter rainfall region of the Fynbos Biome and may aid similar initiatives elsewhere.

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